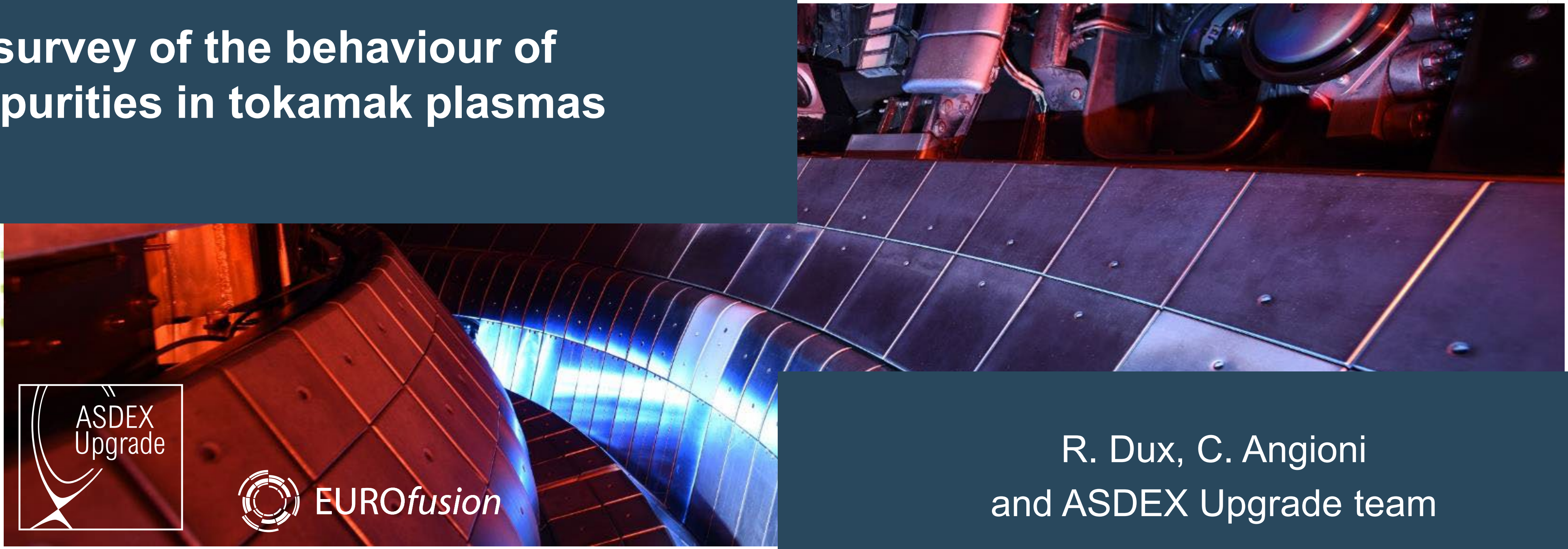
MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

A survey of the behaviour of impurities in tokamak plasmas



R. Dux, C. Angioni
and ASDEX Upgrade team

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Outline

- **Sources and main objectives for the different types of impurities**
- **Radial transport of impurities in the confined plasma and resulting profiles**
- **Transport mechanisms in the different parts of the confined plasma (from core to edge)**
- **Conclusions**

Impurity sources

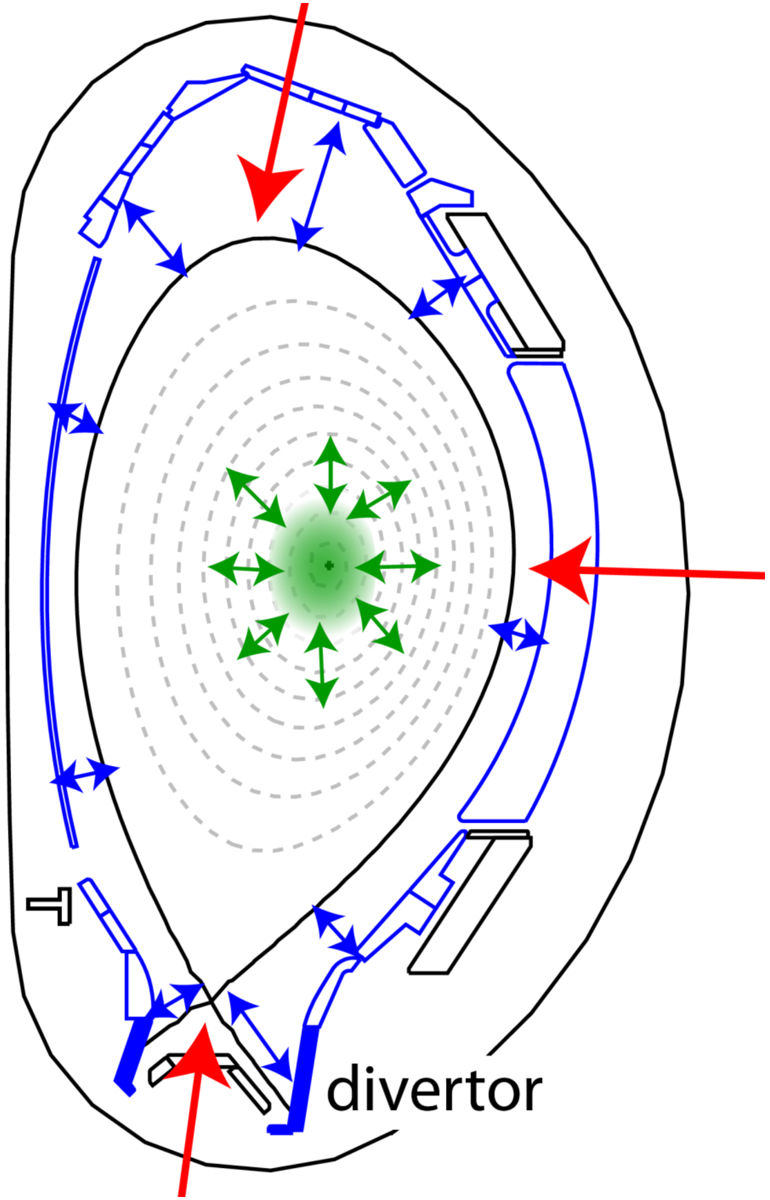
- Erosion at first wall (W, Be, C …)

- Production of He in the core

$$^{2}_{1}D + ^{3}_{1}T \rightarrow ^{4}_{2}He + ^{1}n$$

3.5MeV 14.1MeV

- Intentionally injected impurities to invoke radiation losses (e.g. N, Ne, Ar, Kr, …)



Main objective for He

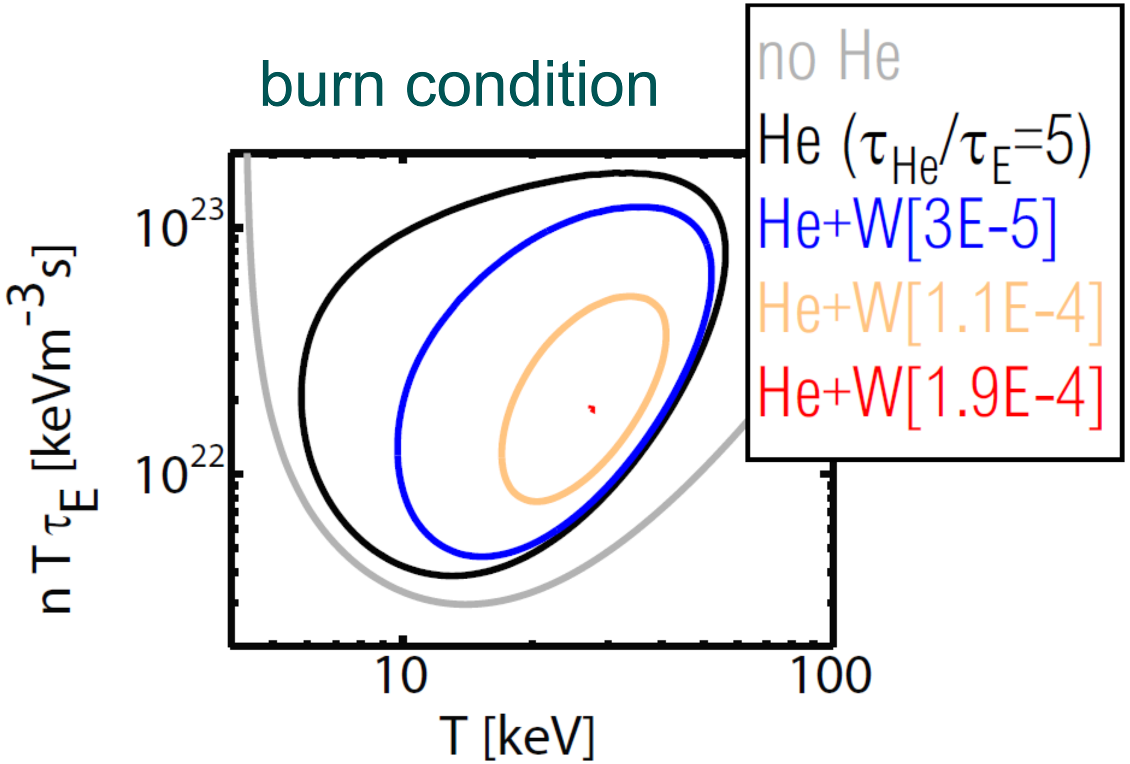
- Low global confinement time

$$\tau_{He}^* = \frac{\int n_{He} dV}{\int n_D n_T \langle \sigma_{fus} v \rangle dV}$$

- Figure of merit:

$$\rho^* = \frac{\tau_{He}^*}{\tau_E}$$

- Optimal impurity transport when
  - Helium profile in confined plasma is hollow
  - strong compression of Helium in divertor area and pump duct (not covered)



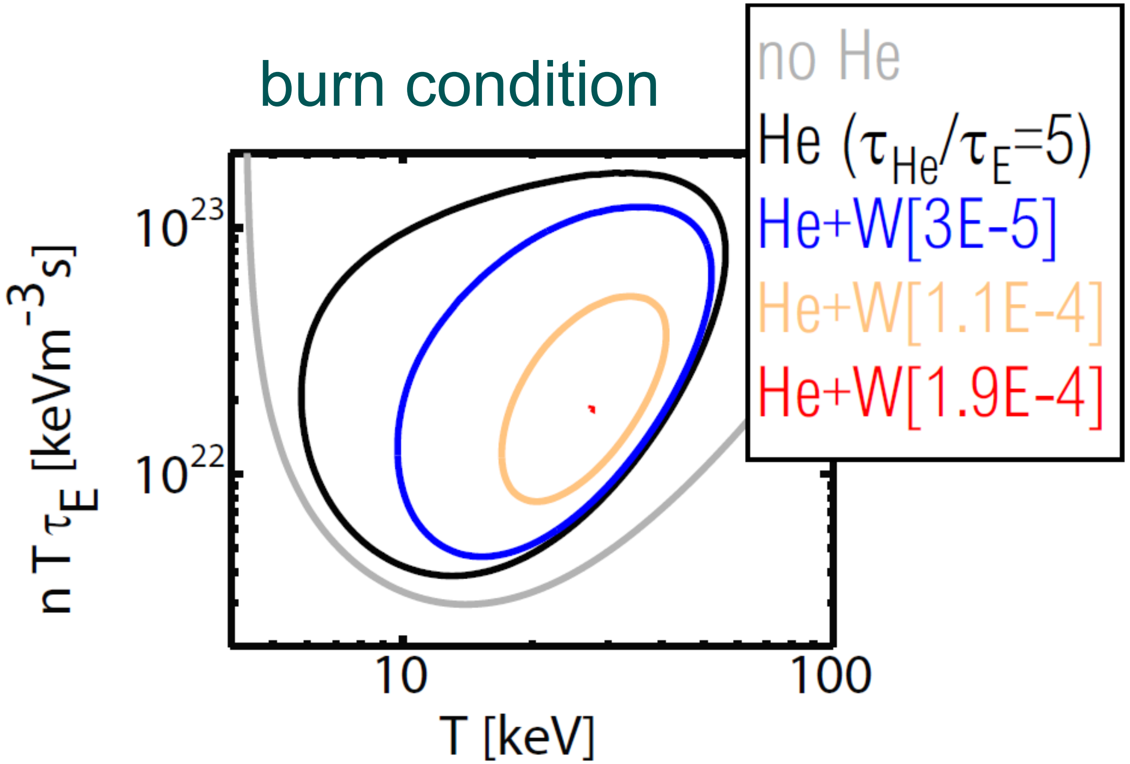
Main objective for W

- Low T_e at wall to have low yield Y_{pW} for sputtering of W by projectile p
- Low W confinement time

$$\tau_W = \frac{\int n_W dV}{\sum_p \int \Gamma_p Y_{p,W} dA}$$

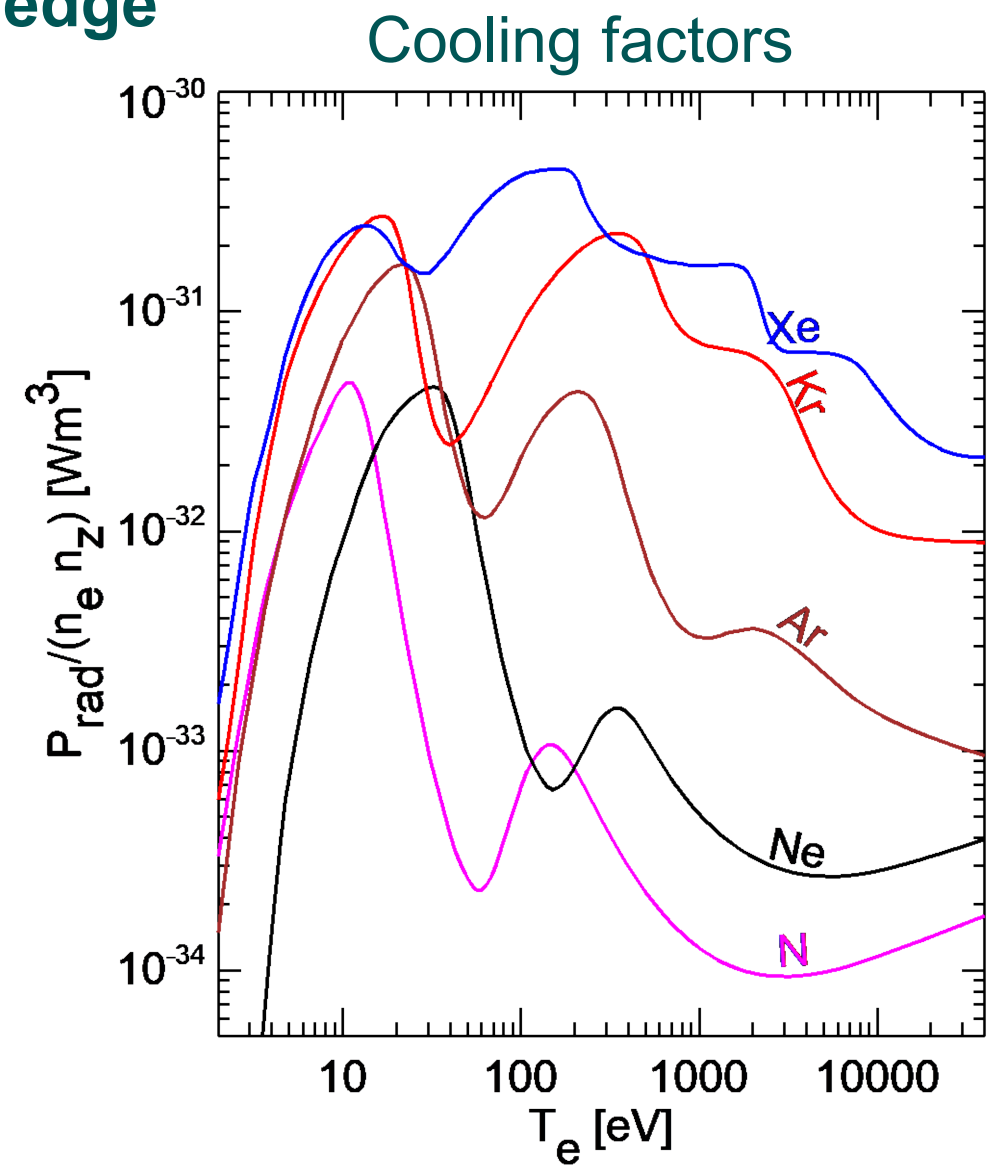
- Figure of merit:
  tungsten concentration in the core

- Optimal impurity transport when
  - strong prompt redeposition of eroded W
  - W profile in confined plasma is hollow



Main objective of injected impurities: Increase radiation losses at the plasma edge

- but little impurity radiation in the centre
- Edge can be the edge of the confined plasma (DEMO), the divertor (ITER) or the X-point region
- Figures of merit:
  - radiation loss at edge / radiation loss in the core
  - radiation loss at edge/ fuel dilution in the core
- Optimal impurity transport when
  - impurity profile in confined plasma hollow
  - strong compression of impurity in divertor area (for divertor radiators, see talk A. Kallenbach)



Equilibrium profile of impurities in the confined plasma

- Radial profile of impurities in temporal equilibrium determined by **v/D**
  v<0 $\rightarrow$ inward drift $\rightarrow$ peaked profile
  v=0 $\rightarrow$ purely diffusive $\rightarrow$ flat profile
  v>0 $\rightarrow$ outward drift $\rightarrow$ hollow profile
- He
  additional peaking in core when D is too low (small effect)
- **Accumulation** (=much stronger peaking of impurity than of main ion) must be avoided

$$\frac{1}{n_z}\frac{\partial n_z}{\partial r} \ll \frac{1}{n_{DT}}\frac{\partial n_{DT}}{\partial r}$$

- Radial Flux

$$\Gamma = -D\frac{\partial n}{\partial r} + vn$$

- Transport equation

$$\frac{\partial n}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(D\frac{\partial n}{\partial r} - vn\right) + Q$$

- Density gradient in temporal equilibrium

$$\frac{1}{n}\frac{\partial n}{\partial r} = \frac{v}{D} \quad - \quad \frac{1}{D}\left(\frac{1}{nr}\int Qrdr\right)$$

He, ...W **He**

Turbulent and collisional transport contribution

neoclassical (collisional) transport

- due to Coulomb collisions between impurity and main species (and other impurity species)

turbulent (anomalous) transport

- due to micro instabilities

$$D = D_{neo} + D_{an}$$

$$v = v_{neo} + v_{an}$$

Next slides

- main effects of the two mechanisms
- regions where one of the two channels dominates

Collisional transport contribution

collisional (neoclassical) transport

- Inward drift with gradient of n_{DT}
- Outward drift with gradient of T_i (temperature screening)
- v/D increases linear with Z

Accumulation of High-Z impurities when neoclassical transport is dominant

- Neoclassical drift

$$\frac{v_{neo}}{D_{neo}} = Z\left(\frac{1}{n_{DT}}\frac{\partial n_{DT}}{\partial r} + H\frac{1}{T_i}\frac{\partial T_i}{\partial r}\right)$$

inward **outward (0 > H > -0.5)**

- Peaking with respect to main ions

$$\frac{\partial \ln(n_z)}{\partial r} = \frac{\partial \ln(n_{DT})}{\partial r} Z\left(1 + H\frac{\partial \ln(T_i)}{\partial \ln(n_{DT})}\right)$$

Turbulent transport contribution

turbulent transport

- present when gradients of T or n exceed a critical value
- Several drift terms (thermo-diffusion, roto-diffusion, pure convection)
- However v/D rather small
  - weakly scales with Z and mass
  - transport mainly due to fluctuating ExB-drifts (ExB-drift does not depend on Z or m)

Accumulation never observed when turbulent transport prevails

- Anomalous drift

$$\frac{v_{an,Z}}{D_{an,Z}} \approx \frac{v_{an,DT}}{D_{an,DT}}$$

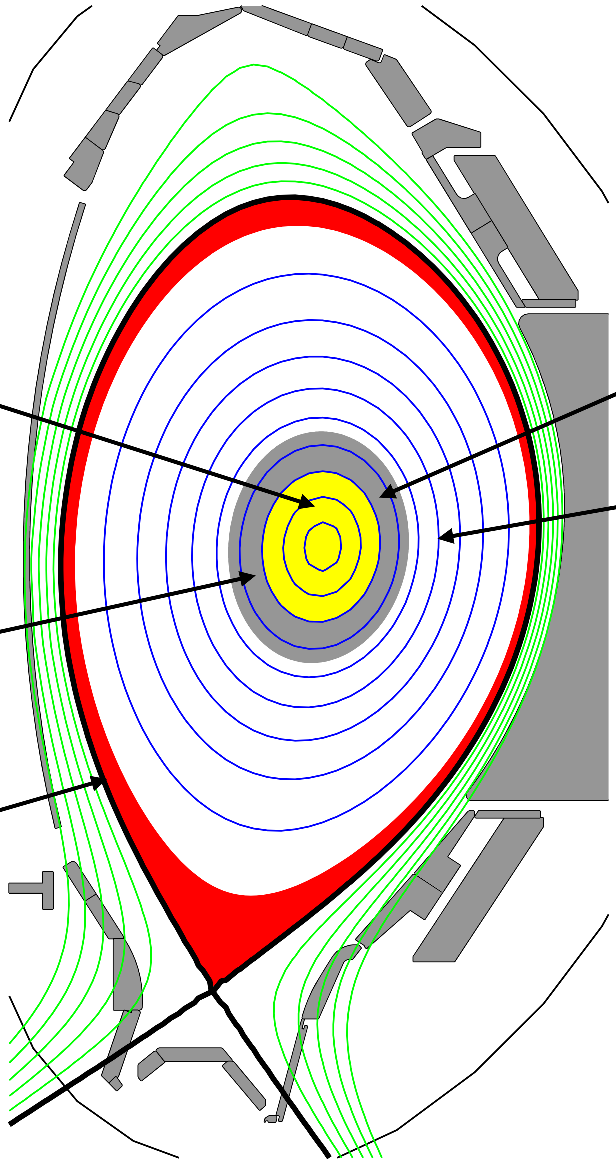
- Peaking with respect to main ions

$$\frac{\partial \ln(n_z)}{\partial r} \approx \frac{\partial \ln(n_{DT})}{\partial r}$$

Collisional impurity transport in the very core and edge

Neoclassical

- Inner core (for all Z)
  - no turbulence
  - gradients of T_e, T_i, n < critical value
  - depends on strength of central heating
- Close to core
  - only for high-Z elements in toroidally rotating plasma
- Edge transport barrier in H-Mode
  - turbulence suppressed
  - collisional for all Z



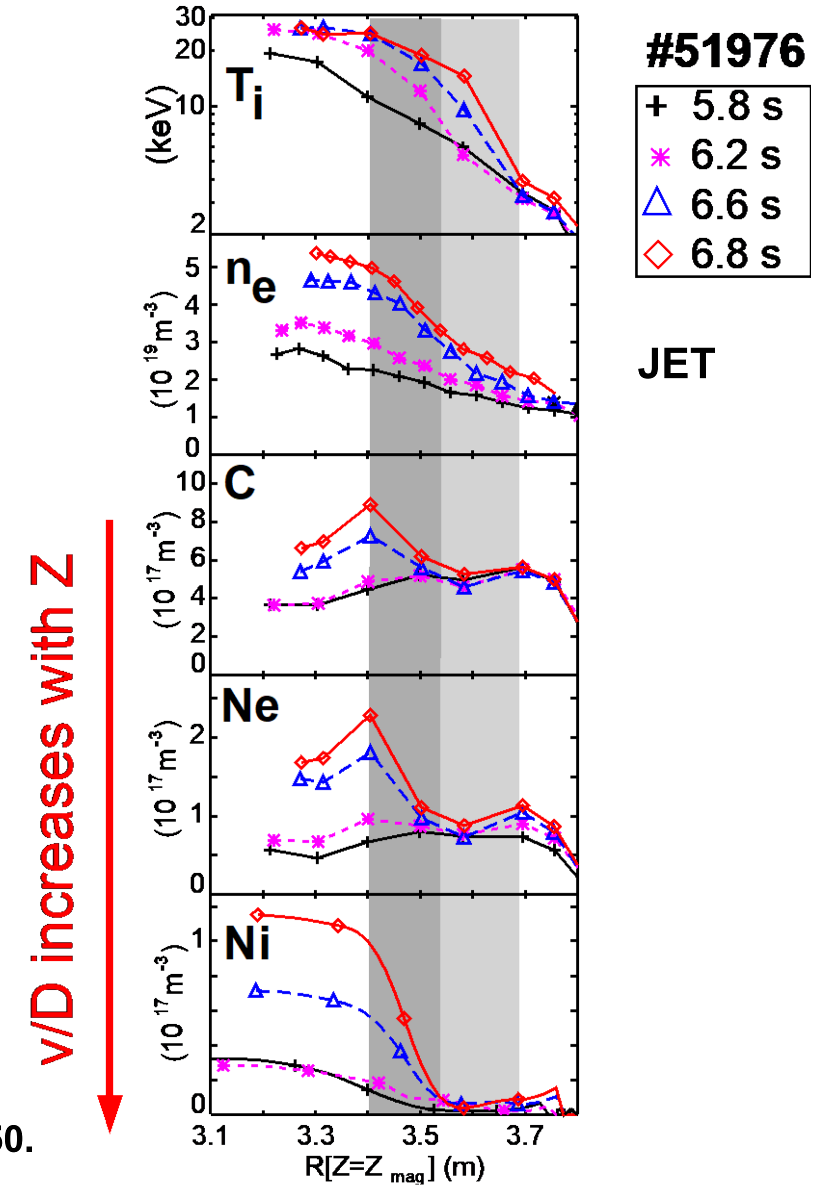
Turbulent

- close to Core
  - for low-Z elements
- confinement region
  - for all Z

Example for dominant neoclassical transport in the core (ITB)
Accumulation for high-Z

For JET plasma with internal transport barrier

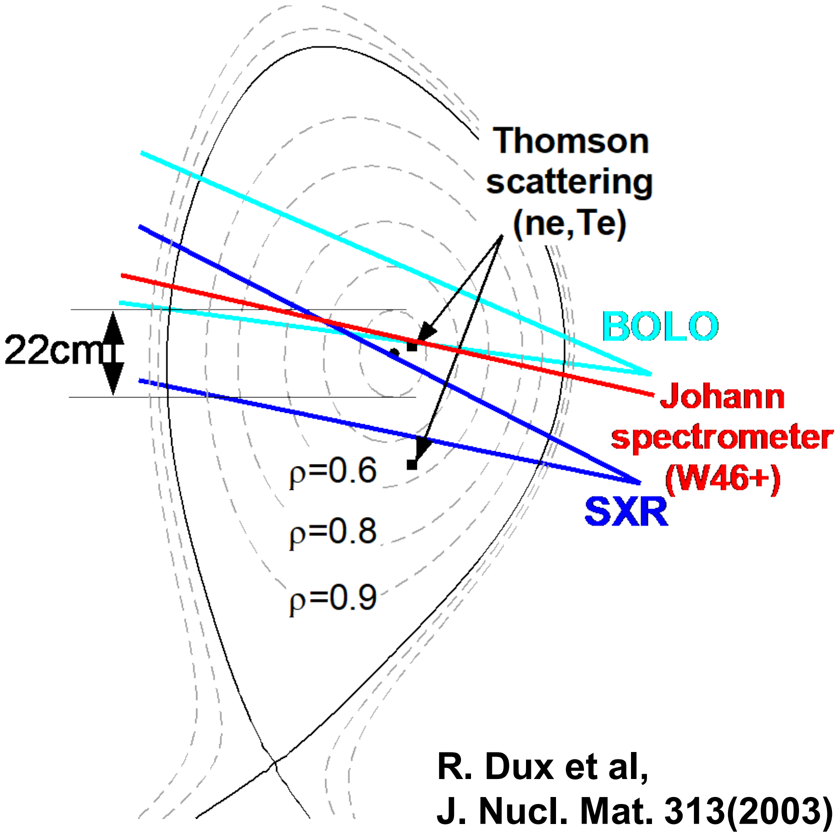
- Strong impurity gradients just inside barrier of T_i
- Here weak T_i gradient but density peaking
- Z-dependence as expected for neoclassical transport



R. Dux et al,
J. Nucl. Mat. 313(2003) 1150.

Suppression of central W accumulation via central ECRH

central heating increases turbulent transport far above collisional transport and accumulation stops



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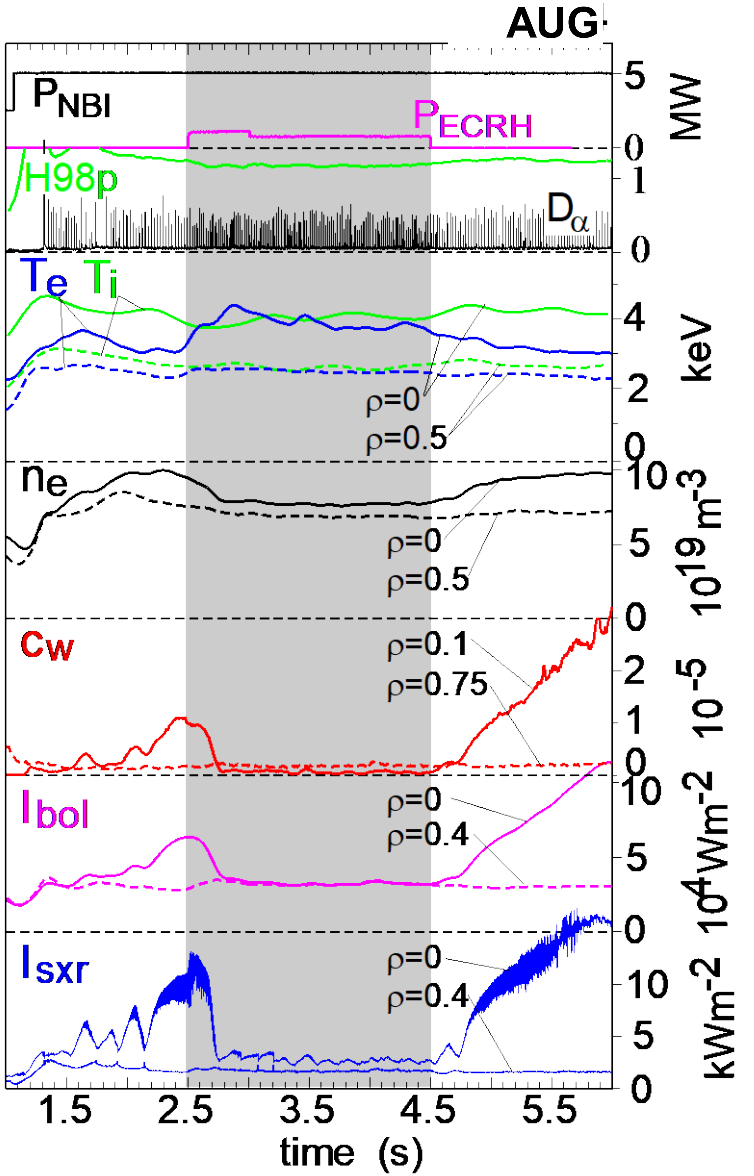
J. Nucl. Mat. 313(2003) 1150.



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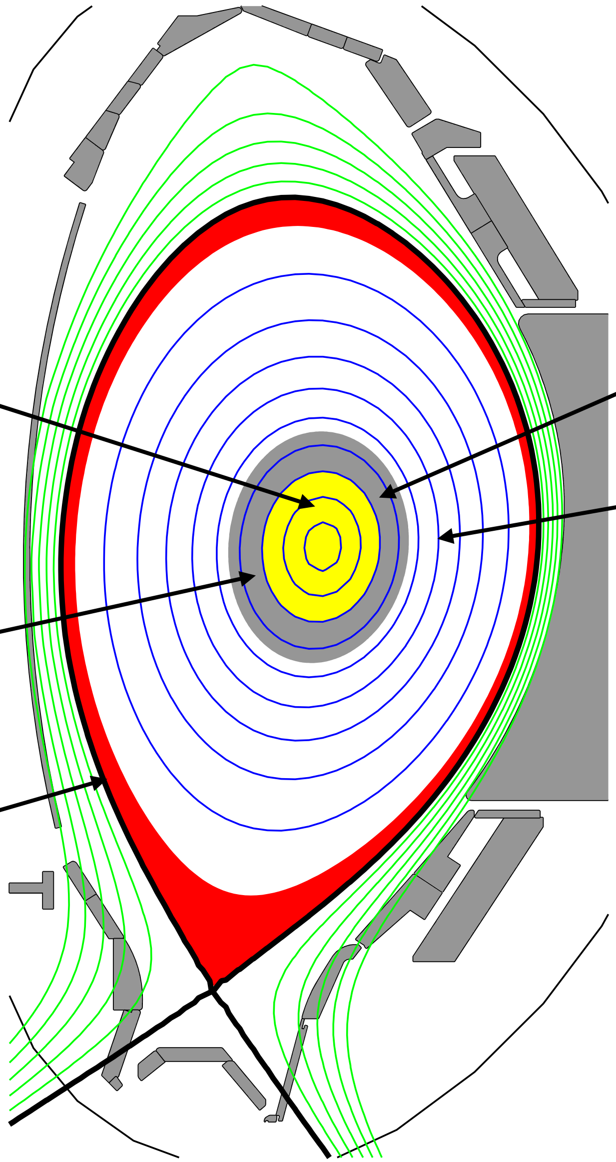


Turbulent

- close to Core
  - for low-Z elements
- confinement region
  - for all Z

Poloidal asymmetry of impurity density on flux surface modifies Pfirsch-Schlüter transport

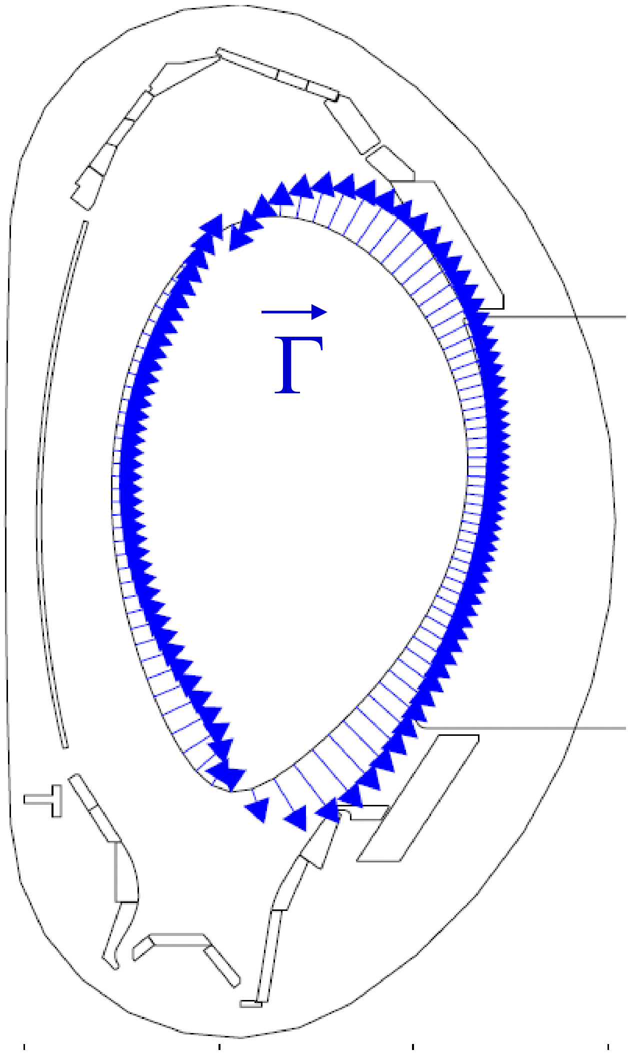
- Pfirsch-Schlüter flux due to friction forces resulting from Pfirsch-Schlüter flows
- Flows and fluxes reverse sign at top and bottom
- Total effect from average along flux surface

constant impurity density on flux surface

- Fluxes at LFS and HFS cancel in lowest order

poloidal asymmetry on flux surface

- No cancelation of fluxes
- Can lead to a strong increase of flux surface averaged PS flux



Poloidal asymmetry only for impurities with large mass and Z

$$\frac{n_z(R_{out})}{n_z(R_{in})} = \exp\left[\frac{m_z\omega^2(R_{out}^2 - R_{in}^2)}{2k_BT_i} - \frac{eZ(\Phi(R_{out}) - \Phi(R_{in}))}{k_BT_i}\right]$$

centrifugal force,
(tor. Mach number)

Potential difference from quasi-neutrality on FS,
(influence of fast ions)

2.5MW NBI

+ 4.3MW ICRH

AUG

- Centrifugal force pushes impurities with large mass to the outboard side and produces a density asymmetry on the flux surface
- only for impurities with large mass
- Poloidal asymmetry of fast ions produces additional potential difference on flux surface (ICRH, NBI)

T. Odstrcil et al (2018) PPCF 60, 014003.

Poloidal asymmetry of W as measured with soft X-ray cameras fits to theoretical predictions

$$\frac{n_z(R_{out})}{n_z(R_{in})} = \exp\left[\frac{m_z\omega^2(R_{out}^2 - R_{in}^2)}{2k_BT_i} - \frac{eZ(\Phi(R_{out}) - \Phi(R_{in}))}{k_BT_i}\right]$$

centrifugal force,
(tor. Mach number)

Potential difference from quasi-neutrality on FS,
(influence of fast ions)

AUG

- Agreement of observed and calculated asymmetry

T. Odstrcil et al (2018) PPCF 60, 014003.

Increase of Pfirsch-Schlüter transport for higher W density at outboard side

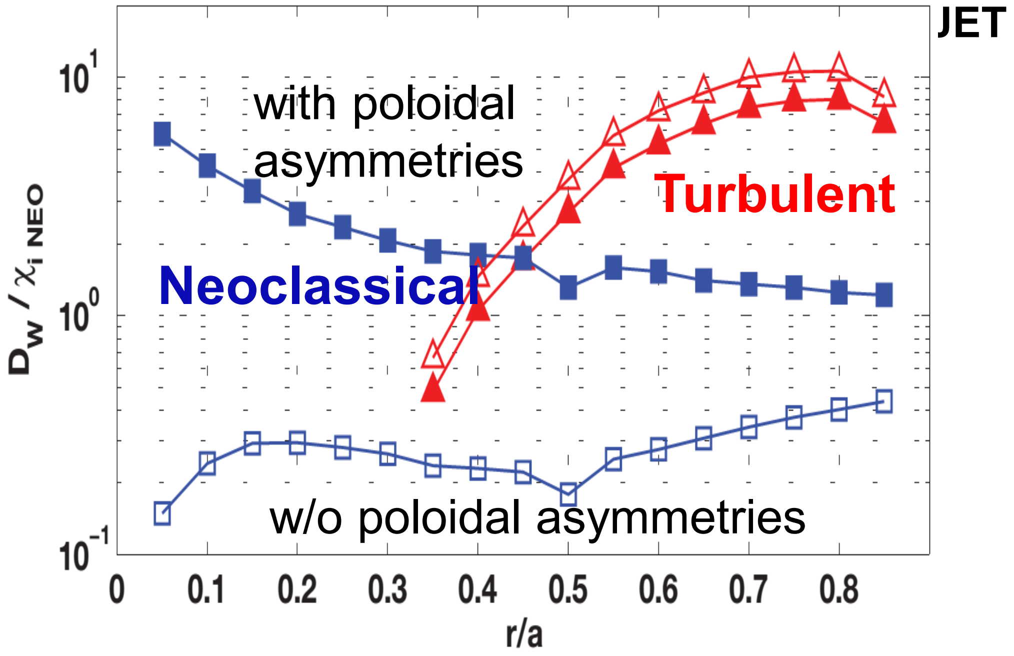
- Enhancement of Pfirsch-Schlüter diffusion coefficient

$$D_{PS} = 2q^2 D_{CL} P_A$$

$$P_A = \frac{1}{2\epsilon^2} \frac{\langle B^2 \rangle}{\langle n_z \rangle} \left[\left\langle \frac{n_z}{B^2} \right\rangle - \left\langle \frac{B^2}{n_z} \right\rangle^{-1} \right]$$

- temperature screening
  - decreases for high ν*
  - increases for low ν*

Increase of the PS transport of W in JET plasmas with 17MW NBI (up to a factor of 20)

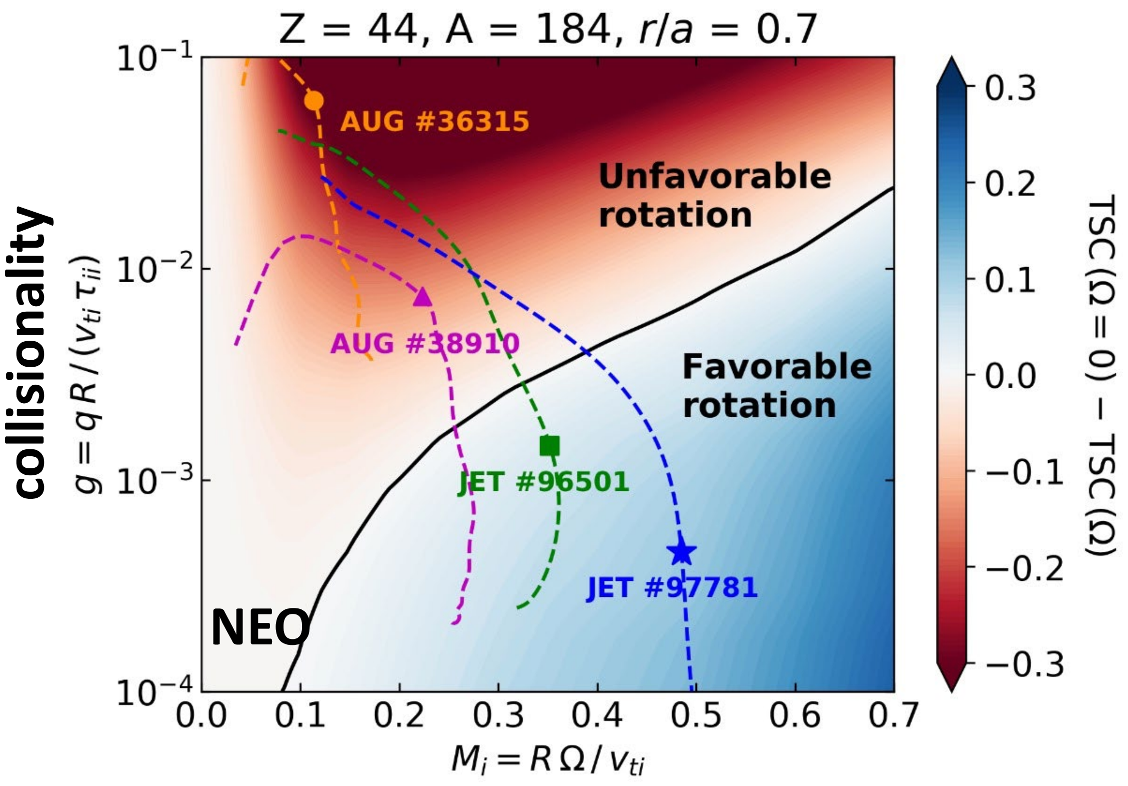


C. Angioni et al (2015) Phys. Plasmas 22, 055902.

Increased temperature screening for higher W density at outboard side when collisionality is low

In a fast rotating plasma:

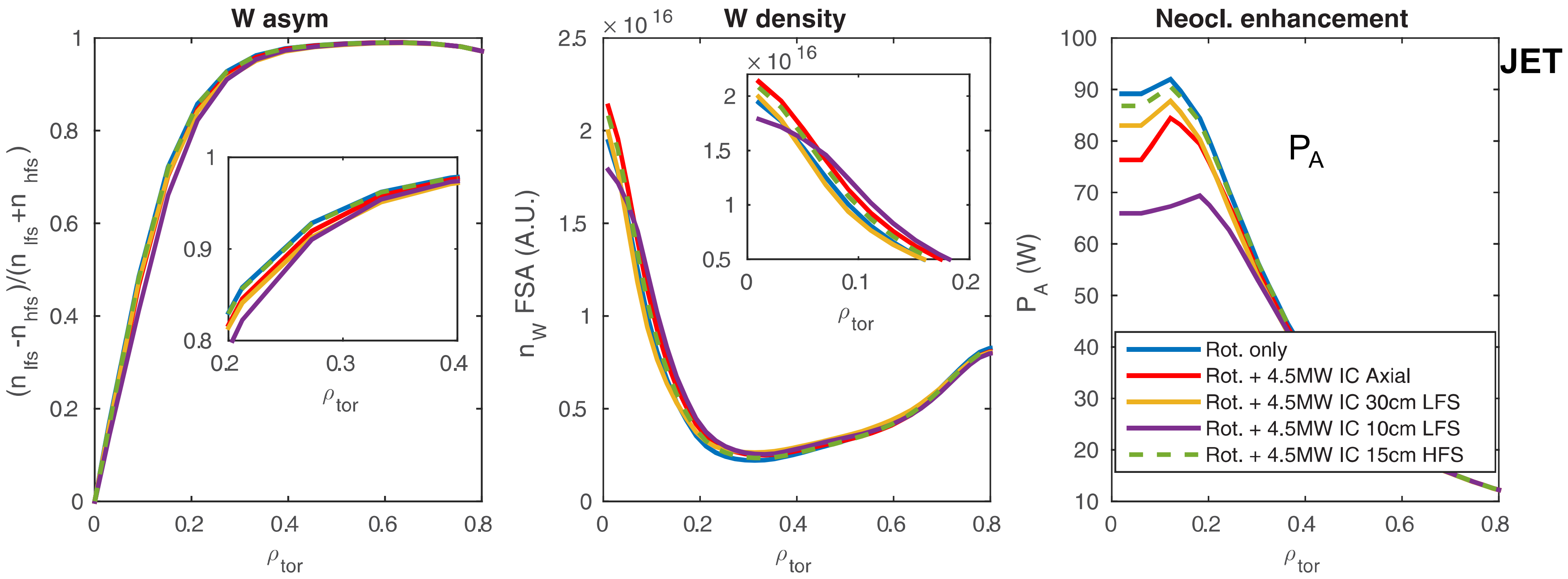
- temperature screening (=outward convection due to T_i-gradient) decreases with collisionality
- Compared to v_{tor}=0 the total v_{neo} is
  - more inwardly directed in AUG
  - more outwardly directed in hot JET plasmas (and in a burning plasma)



D. Fajardo et al (2022) to be subm. to PPCF

Increase of Pfirsch-Schlüter transport for higher W density at outboard side

Example for the increase of the PS transport of W in JET plasma with 26MW NBI (up to a factor of 100)



F. J. Casson et al (2020) Nucl. Fus. 60, 066029.

Increase of Pfirsch-Schlüter transport also found in direct measurements

AUG

- Measured dependence of diffusion coefficient of tungsten on poloidal asymmetry confirms this increase
- agreement with neoclassical theory within factor 2-3

neo

In a large burning tokamak plasma

- Low toroidal rotation due to small momentum source (α-heating with small addition of external heating)
- PS transport of high-Z elements again small

$$\delta_{sxr} = \frac{\epsilon_{sxr}(R_{out}) - \langle \epsilon_{sxr} \rangle}{\langle \epsilon_{sxr} \rangle}$$

T. Odstrcil, et al (2018) PPCF 60, 014033.

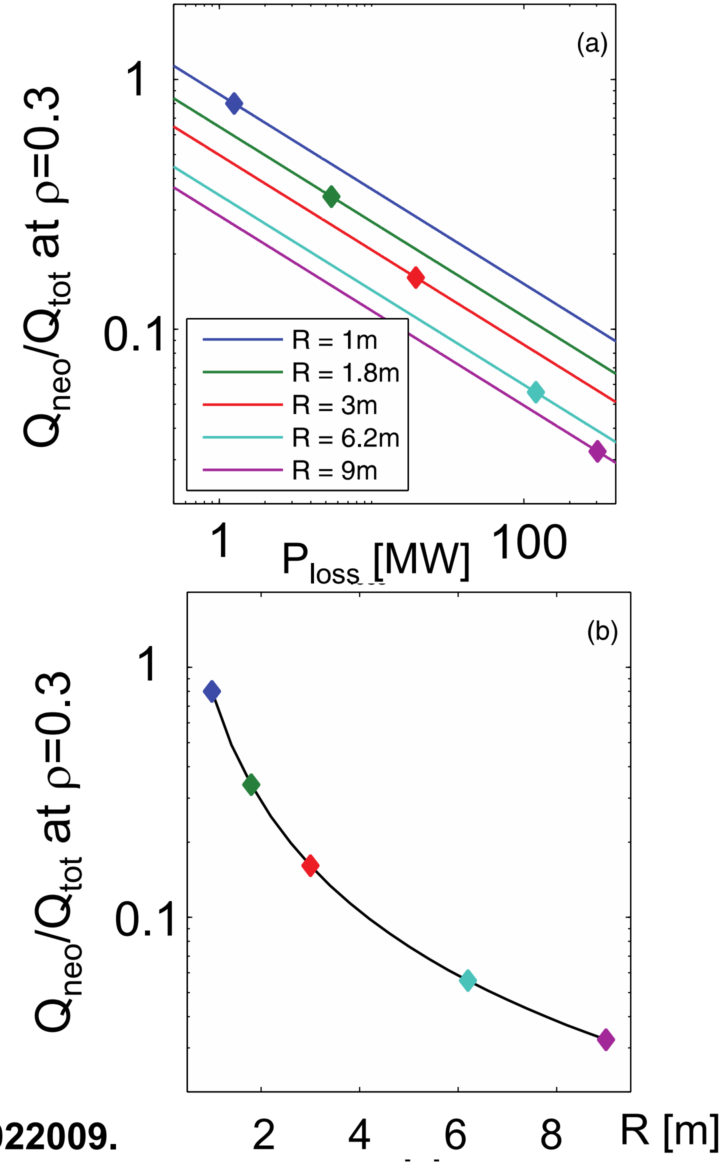
Heat transport is more turbulent in larger tokamaks

Rescale ITER standard scenario

- At constant R/a, I_p/a^2, n/n_{GW}, RB_t/I_p
- Use $\tau_{E,IPB98}$ to get T for given P_{heat}
- ½ of P_{heat} inside $\rho=r/a=0.3$
- Calculate Q_{neo} and compare with Q_{tot}

For typical heating powers in the large tokamaks

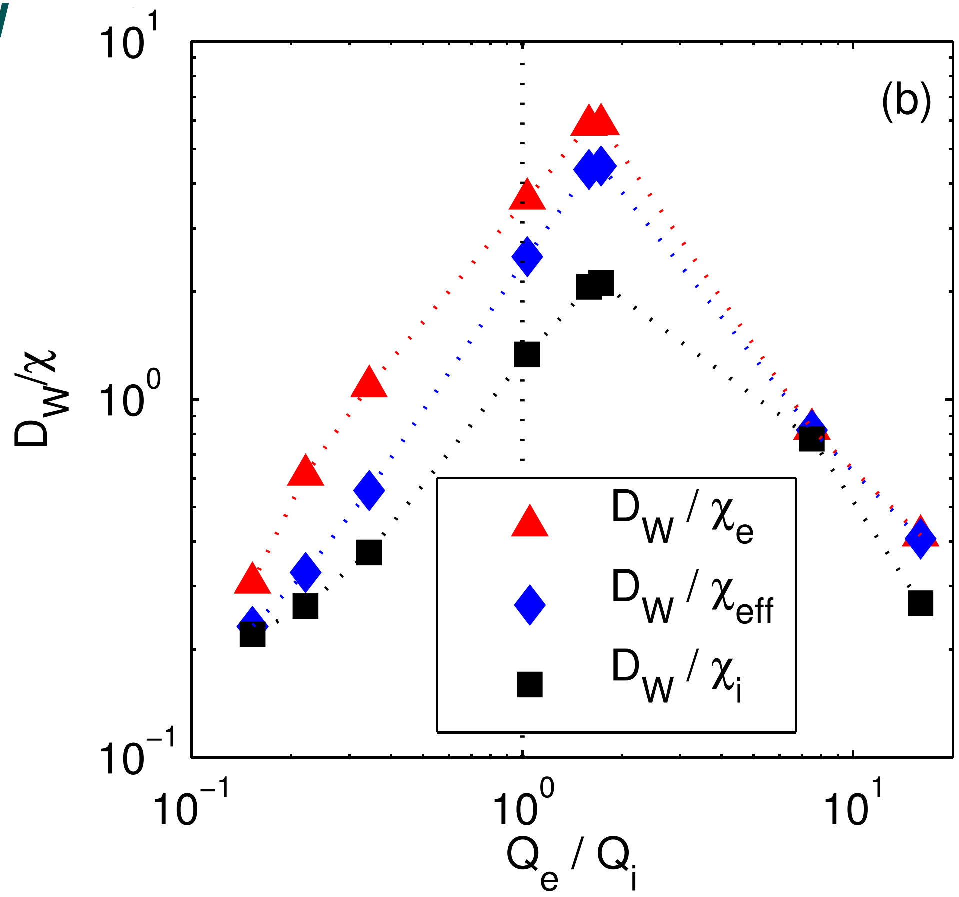
- Heat transport is much stronger dominated by turbulent transport than in smaller machines
- Coefficient of turbulent impurity diffusion will be even higher than that of heat diffusion (next slides)



C. Angioni et al, NF 57 (2017) 022009.

Turbulent impurity diffusion coefficient is larger than the ion heat diffusion coefficient at $Q_e \approx Q_i$

- **Set of nonlinear gyro-kinetic simulations with GKW**
  - T_i=const. , Q_e+Q_i=const.
  - vary R/LT_e, R/LT_i, T_e/T_i to change Q_e/Q_i
  - Z_W = 41
- **W diffusion: D_W/χ**
  - <<1 for Q_e>>Q_i (TEM) and Q_i>>Q_e (ITG)
  - maximum >> 1 for Q_e = (1-2)Q_i
- **Same result from linear runs**
  - maximum of D_W/χ when real mode frequency is slightly above zero



C. Angioni et al, Phys. Plas. 22 (2015) 102501.

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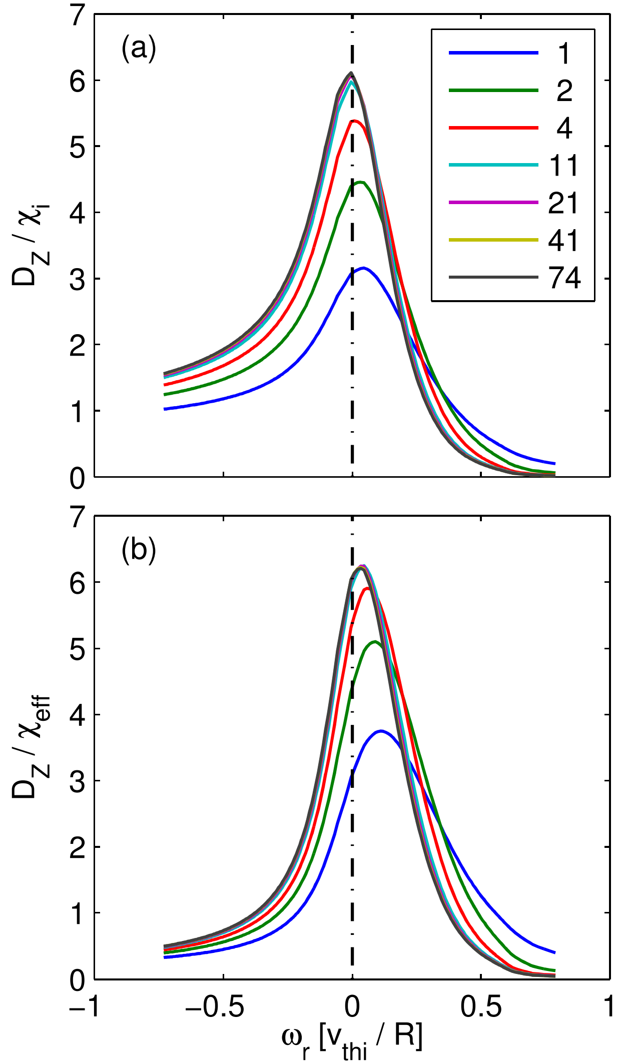
- **W diffusion: D_W/χ**
  - <<1 for Q_e>>Q_i (TEM) and Q_i>>Q_e (ITG)
  - maximum >> 1 for $Q_e = (1\text{-}2)Q_i$
- **Same result from linear runs**
  - maximum of D_W/χ when real mode frequency is slightly above zero
- **and from quasi-linear analytical description**
  - also for low-Z impurities

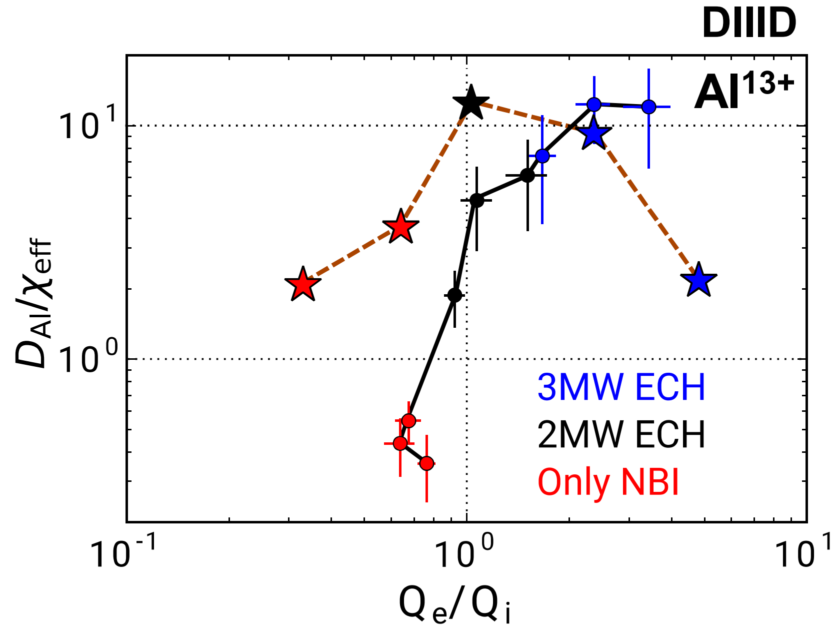
C. Angioni et al, Phys. Plas. 22 (2015) 102501.



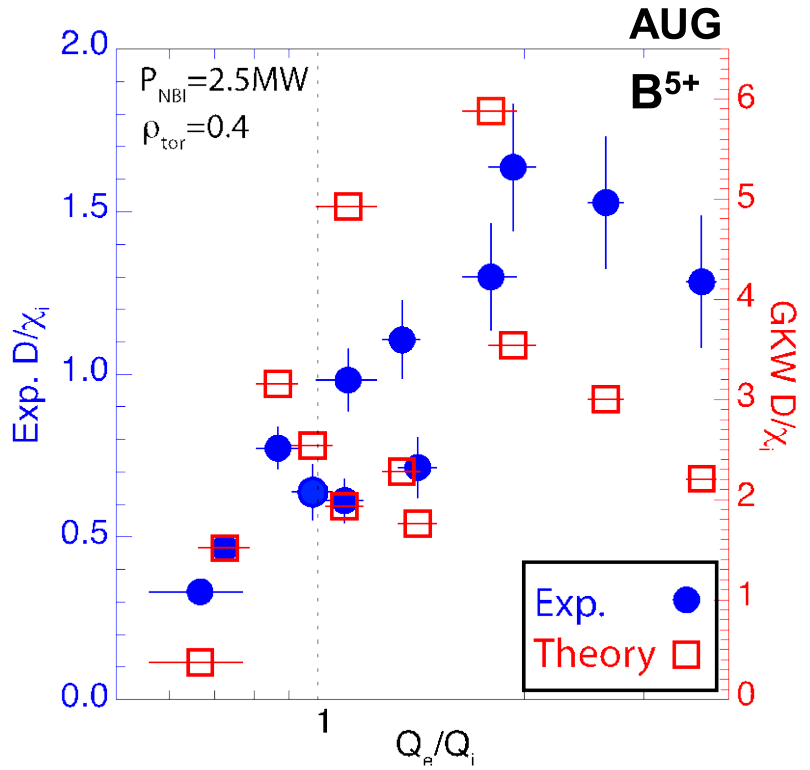
$\approx Q_i/Q_e$

Turbulent impurity diffusion coefficient is larger than the ion heat diffusion coefficient at $Q_e \approx Q_i$

Recent impurity transport measurement also show this trend of D_z/χ_{eff} with Q_e/Q_i



T. Odstrcil et al, Phys. Plas. 59 (2020) 082503.

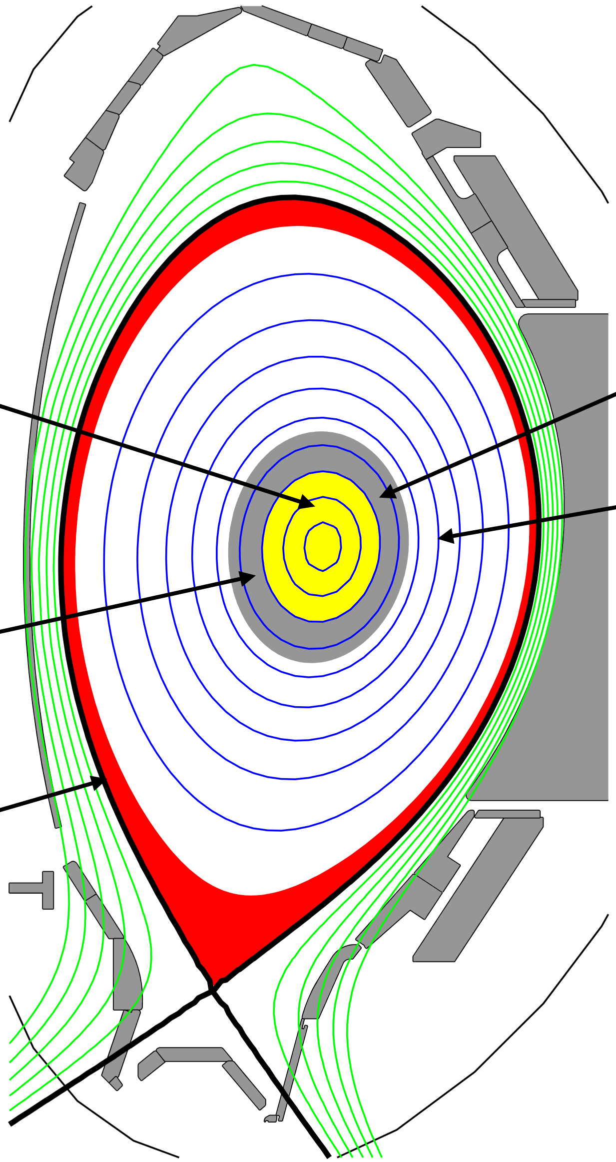


R. McDermott et al, Nucl. Fus. 62 (2022) 026006.

Collisional impurity transport in the very core and edge

Neoclassical

- Inner core (for all Z)
  - no turbulence
  - gradients of T_e, T_i, n < critical value
  - depends on strength of central heating
- Close to core
  - only for high-Z elements in toroidally rotating plasma
- Edge transport barrier in H-Mode
  - turbulence suppressed
  - collisional for all Z



Turbulent

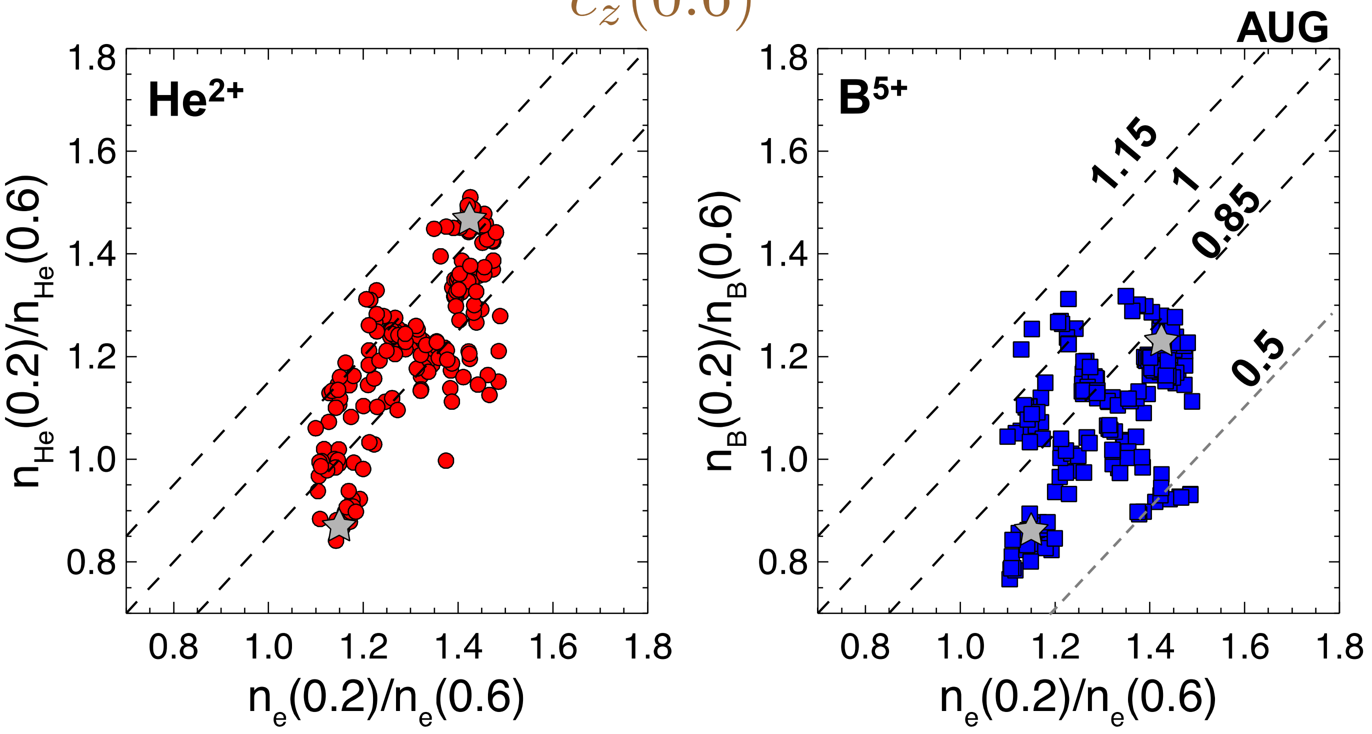
- close to Core
  - for low-Z elements
- confinement region
  - for all Z

No accumulation due to turbulent transport

Equilibrated density profiles of He^{2+} and B^{5+} as measured by CXRS are

- either a bit more peaked than n_e
- or hollow
- but never much stronger peaked than n_e

$$0.5 \leq \frac{c_z(0.2)}{c_z(0.6)} \leq 1.15$$

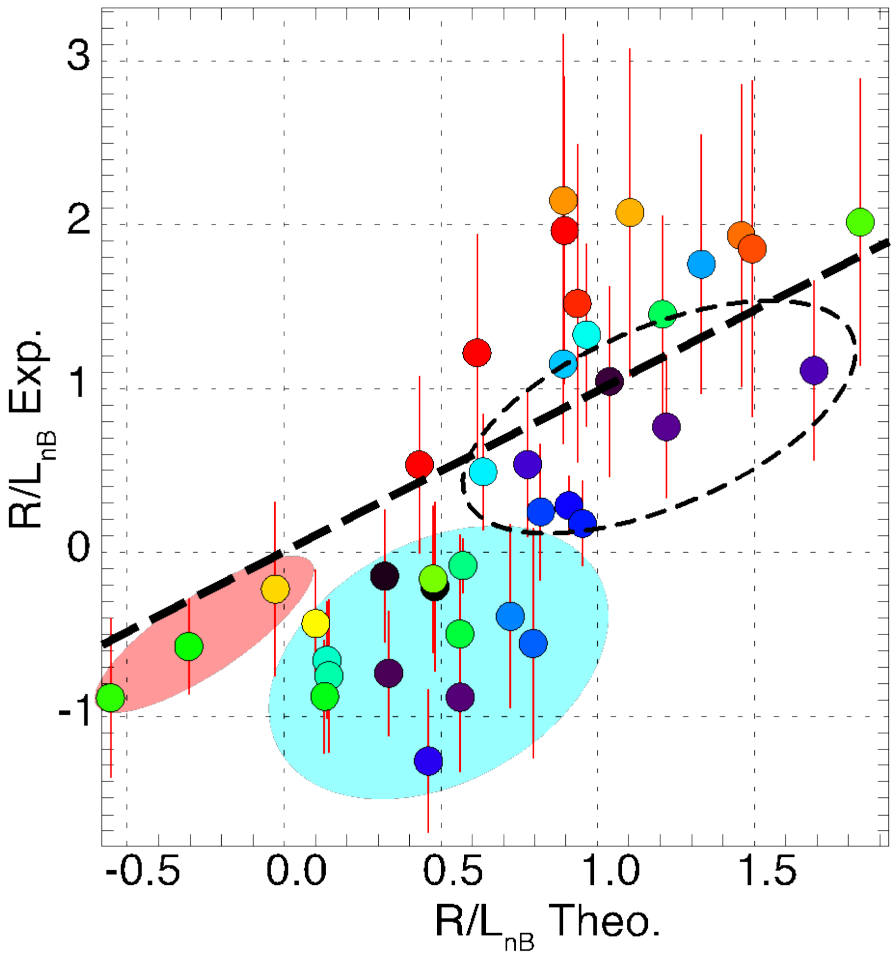


A. Kappatou et al, Nucl. Fus. 59 (2019) 056014.

No accumulation due to turbulent transport

Agreement with calculated gradients is often good but not in all cases

- the cases with hollow boron profiles are below the theoretical values outside the error margin



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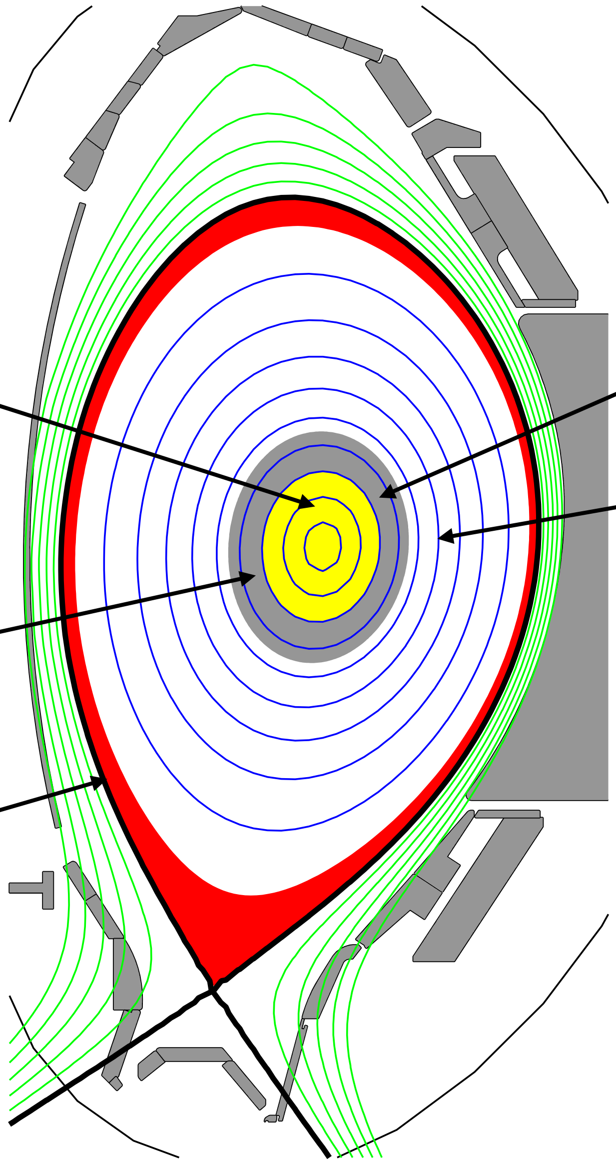


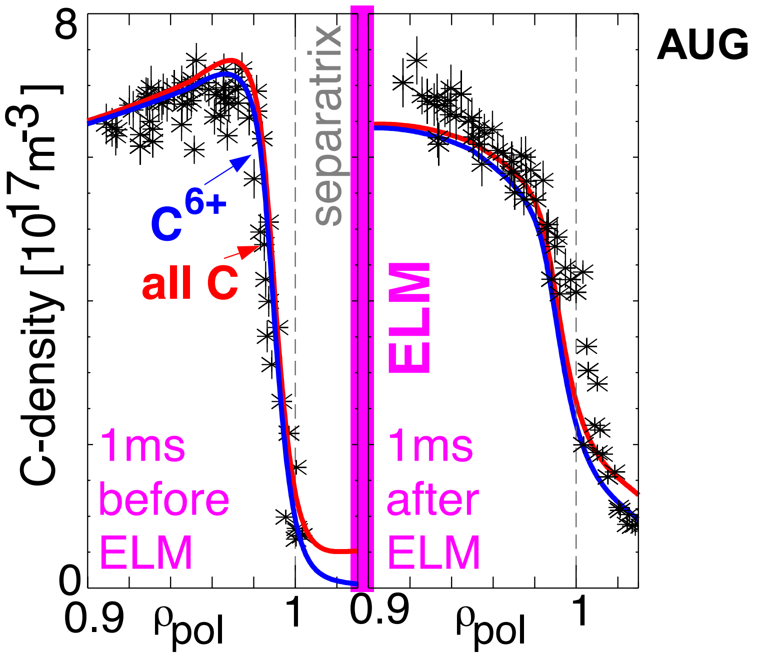
Turbulent

- close to Core
  - for low-Z elements
- confinement region
  - for all Z

Neoclassical impurity transport in the edge transport barrier (ETB)

CXRS measurement of impurity profile evolution in the plasma edge during ELM cycle

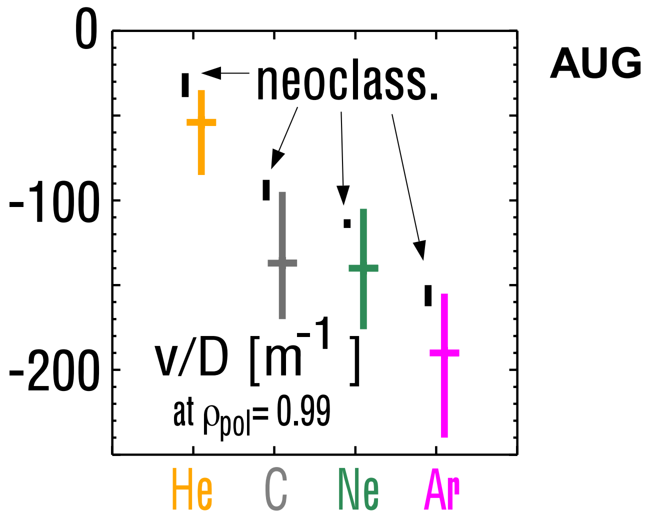
- He, C, Ne and Ar
- peaking of impurity density in ETB between ELMs
- peaking increases with Z
- flattening of gradient during ELM



T. Pütterich et al, J. Nucl. Mater. 415 (2011) S334.

Neoclassical impurity transport in the edge transport barrier (ETB)

- transport coefficients D and v in accordance with collisional transport
- v is always inwardly directed
- collisionality of impurities in Pfirsch-Schlüter regime



W has even higher Z in ETB:

- higher collisionality and collisional diffusion
- stronger peaking

T. Pütterich et al, J. Nucl. Mater. 415 (2011) S334.

Outward transport due to edge MHD modes (e.g. ELM‘s) is needed to control the impurity content

Neoclassical impurity transport of W in the ETB of ITER

Neoclassical drift velocity

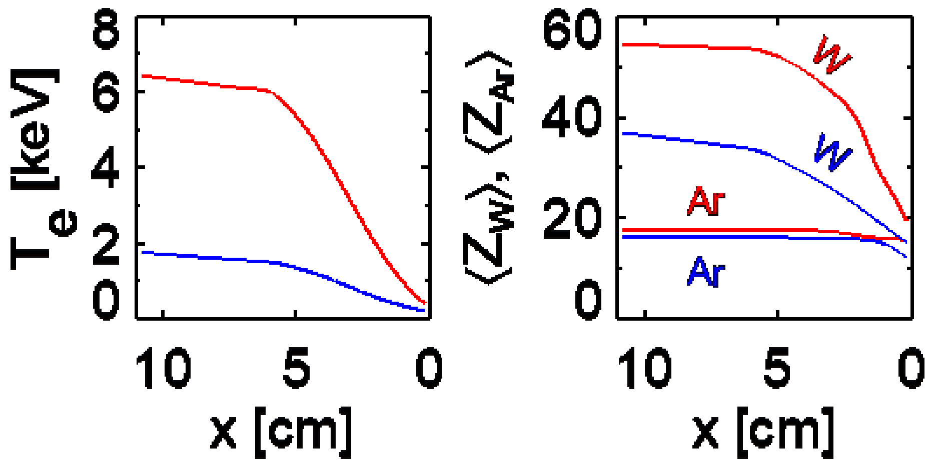
$$\frac{v_{neo}}{D_{neo}} = Z\left(\frac{1}{n_{DT}}\frac{\partial n_{DT}}{\partial r} + H\frac{1}{T_i}\frac{\partial T_i}{\partial r}\right)$$

- Z of W is high
- n_{DT} gradient $\rightarrow$ inward
- T_i gradient for ν^*< 200 H≈-0.5 $\rightarrow$ outward
- Rise of T_i is large

W density across pedestal in temporal equilibrium

$$f_W = \frac{n_W(r_{top})}{n_W(r_{edge})} = \exp\left[\int_{r_{edge}}^{r_{top}} \frac{v_{neo}dr}{D_{neo}}\right]$$

- strongly non-linear function of Z



R. Dux et al, PPCF 56 (2014) 124003.

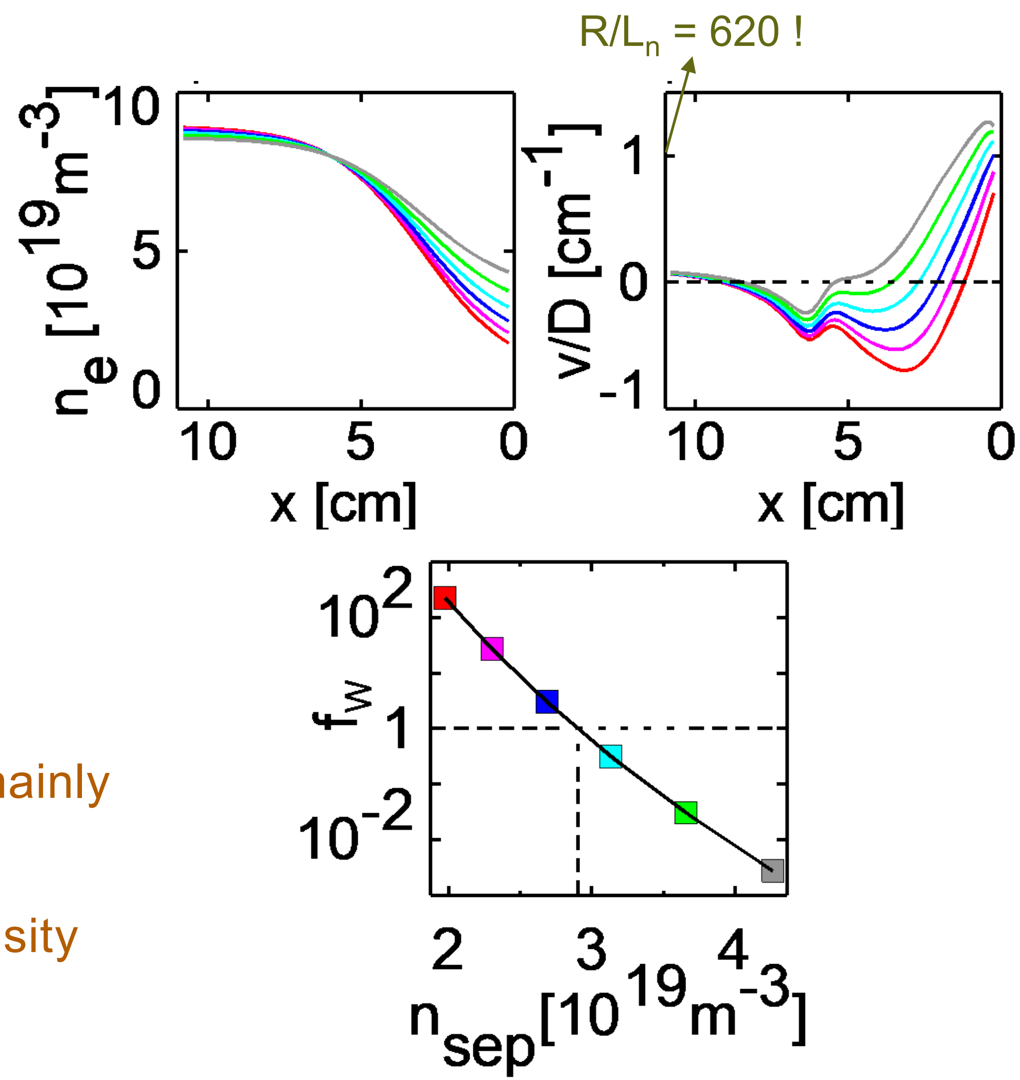
Neoclassical impurity transport of W in the ETB of ITER helps to maintain low W concentrations

ITER ETB – scan of n_{sep}

- Q=10 B=5.3T I_p=15MA
- T_{ped}=4.5 keV, T_{sep}=300 eV
- $n_{ped}=8.5\times10^{19}m^{-3}$
- $n_{sep}=(2\text{-}4.3)\times10^{19}m^{-3}$
- v_{neo}, D_{neo} from NEOART code

W density across pedestal in temporal equilibrium

- for separatrix densities in the range of $(3\text{-}4)\times10^{19}m^{-3}$ (needed for power exhaust) the drift is mainly outward
- neoclassical transport provokes a decrease of the W density from the separatrix to the inside



R. Dux et al, PPCF 56 (2014) 124003.

Conclusion
impurity transport less problematic in a large burning plasma

- **Reduced danger of central accumulation of high-Z elements**
  - no increase of PS-transport due to large toroidal rotation
  - impurity transport more turbulent

- **Turbulent diffusion in confinement area never leads to strong peaking**
  – often the profiles are more hollow than predicted by theory

- **ETB: for pedestal profiles as needed to achieve fusion and a cold divertor**
  - large T_i rise and high n_{sep}
  - neoclassical transport provokes hollow impurity profiles

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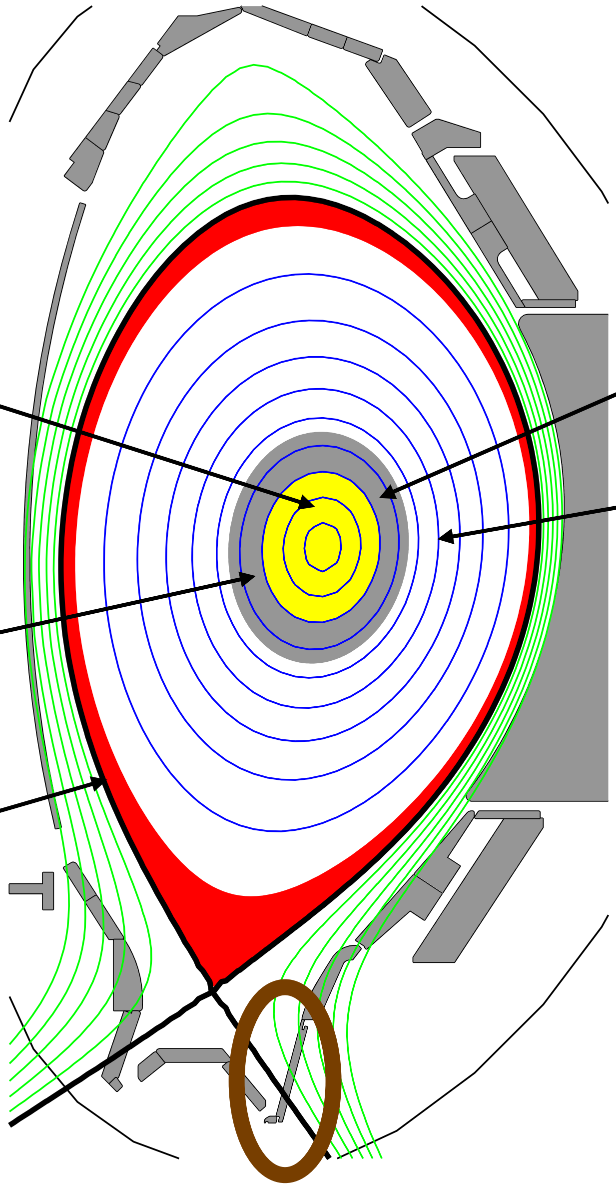


Turbulent

- close to Core
  - for low-Z elements
- confinement region
  - for all Z

Net W source much lower than gross erosion due to prompt redeposition

Characteristic lengths

- Ionisation lengths of W, W⁺

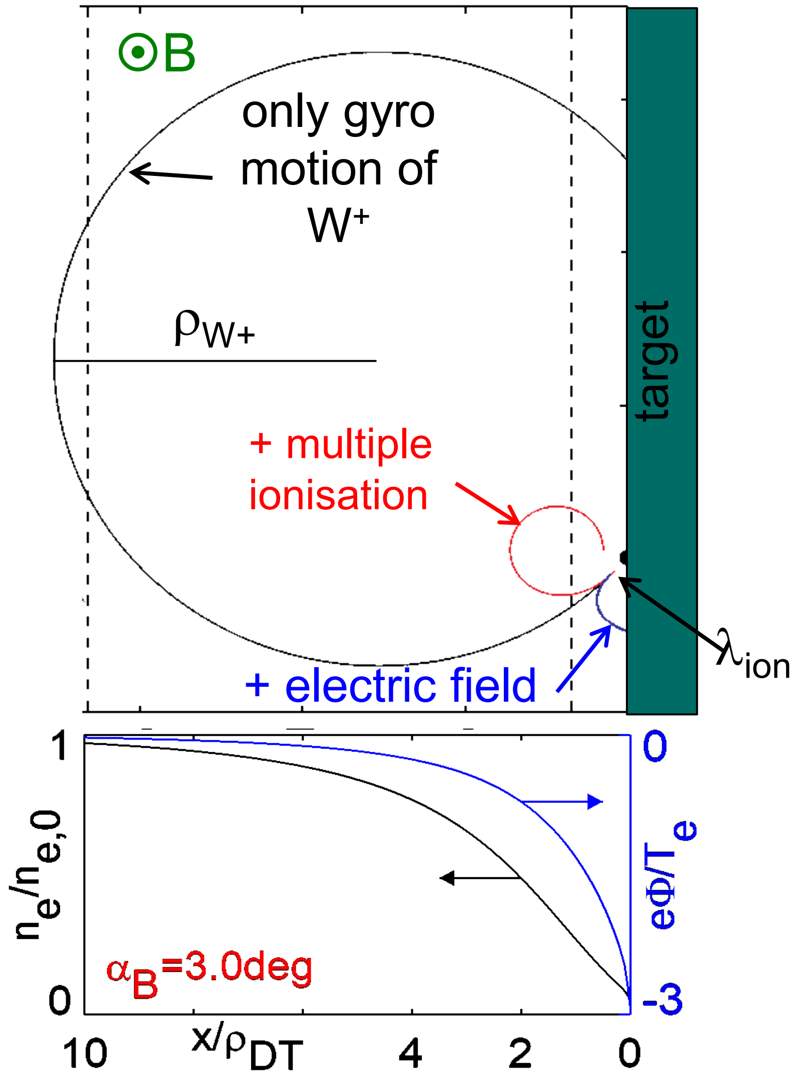
$$\lambda_{ion} = \frac{v}{S_{0\rightarrow1}(T_e)n_e} \qquad \lambda^{+}_{ion} = \frac{v}{S_{1\rightarrow1}(T_e)n_e}$$

- Max. Larmor radius of W⁺

$$\rho_{W+,max} = \frac{v m_W}{eB}$$

- width of magnetic pre-sheath

$$w_{MPS} \approx 5\rho_{DT} = 5\frac{\sqrt{2Tm_{DT}}}{eB}$$



Important effects for W redeposition:

- $\lambda_{ion} > w_{MPS} \rightarrow$ gyro motion of W⁺
- $\lambda_{ion}^{+} < \rho_{W+,max} \rightarrow$ multiple ionisation
- $\lambda_{ion} < w_{MPS} \rightarrow$ electric field

for ELMs in ITER the fraction of non-redepositing W is < 10^{-3} !

A. Chankin et al, PPCF 56 (2014) 025003.
P. C. Stangeby, Nucl. Fus. 52(2012) 083012.